

## CONTENTS

FIGURES.....	viii
TABLES .....	x
TERMS AND DEFINITIONS.....	xi
ABSTRACT .....	1
1. INTRODUCTION AND OVERVIEW .....	2
2. SAMPLING .....	3
2.1 Temporal Indexing of Original and Processed Video Files .....	4
2.2 Spatial Indexing of Original and Processed Video Frames .....	4
2.3 Specifying Rectangular Sub-Regions.....	5
2.4 Considerations for Video Sequences Longer Than 10 Seconds .....	6
3. CALIBRATION.....	6
3.1 Spatial Registration .....	7
3.1.1 Overview .....	7
3.1.2 Interlace Issues .....	8
3.1.3 Required Inputs to the Spatial Registration Algorithm.....	9
3.1.4 Sub-Algorithms Used by the Spatial Registration Algorithm.....	10
3.1.5 Spatial Registration Using Arbitrary Scenes .....	11
3.1.6 Spatial Registration Using Special SMPTE Color Bars .....	16
3.1.7 Spatial Registration of Progressive Video .....	20
3.2 Valid Region .....	21
3.2.1 Core Valid Region Algorithm.....	21
3.2.2 Applying the Core Valid Region Algorithm to a Video Sequence.....	22
3.2.3 Comments on Valid Region Algorithm.....	23
3.3 Gain and Offset .....	23
3.3.1 Core Gain and Level Offset Algorithm.....	23
3.3.2 Using Special SMPTE Color Bars .....	24
3.3.3 Using Scenes .....	26
3.3.4 Applying Gain and Level Offset Corrections .....	27
3.4 Temporal Registration.....	27
3.4.1 Sequence-Based Algorithm for Estimating Constant Temporal Delays between Original and Processed Video Sequences .....	28
3.4.2 Frame-Based Algorithm for Estimating Variable Temporal Delays between Original and Processed Video Sequences .....	42
3.4.3 Sequence-Based vs. Frame-Based Temporal Registration.....	46
3.4.4 Applying Temporal Registration Correction .....	46
4. QUALITY FEATURES.....	47
4.1 Introduction .....	47
4.1.1 Averaging Multiple Video Frames.....	47
4.1.2 S-T Regions.....	48
4.2 Features Based on Spatial Gradients.....	49

4.2.1	Edge Enhancement Filters.....	50
4.2.2	Description of Features $f_{SI13}$ and $f_{HVI3}$ .....	51
4.3	Features Based on Chrominance Information .....	53
4.4	Features Based on Contrast Information .....	53
4.5	Features Based on Absolute Temporal Information (ATI) .....	54
4.6	Features Based on the Cross Product of Contrast and Absolute Temporal Information .....	54
5.	QUALITY PARAMETERS.....	54
5.1	Introduction .....	54
5.2	Comparison Functions.....	55
5.2.1	Error Ratio and Logarithmic Ratio .....	55
5.2.2	Euclidean Distance.....	56
5.3	Spatial Collapsing Functions.....	56
5.4	Temporal Collapsing Functions .....	57
5.5	Nonlinear Scaling and Clipping .....	60
5.6	Parameter Naming Convention .....	60
5.6.1	Example Parameter Names .....	63
6.	VQM MODELS .....	64
6.1	Television VQM ( $VQM_T$ ) .....	65
6.2	Videoconferencing VQM ( $VQM_V$ ) .....	66
6.3	General VQM ( $VQM_G$ ) .....	67
6.4	Developer VQM ( $VQM_D$ ) .....	68
6.5	Peak-Signal-to-Noise-Ratio VQM ( $VQM_P$ ) .....	69
7.	DESCRIPTION OF SUBJECTIVE DATA SETS .....	69
7.1	Data Set One [32] .....	69
7.2	Data Set Two [11] .....	69
7.3	Data Set Three [32] .....	70
7.4	Data Sets Four to Seven [18] .....	70
7.5	Data Set Eight ([4], [5]) .....	70
7.6	Data Set Nine ([28], [30]) .....	70
7.7	Data Set Ten [21] .....	71
7.8	Data Set Eleven [20] .....	71
8.	ROOT MEAN SQUARE ERROR (RMSE) ANALYSIS.....	71
8.1	Television Model Error .....	72
8.2	Videoconferencing Model Error .....	75
8.3	General Model Error .....	77
8.4	Developer Model Error .....	79
8.5	PSNR Model Error .....	82
9.	ROOT CAUSE ANALYSIS (RCA) .....	85
9.1	Calibration Root Cause Analysis (RCA) .....	85

9.1.1	Calibration RCA from Final Results.....	85
9.1.2	Calibration RCA from Intermediate Results.....	87
9.1.3	Severity of Calibration Problems .....	89
9.2	Impairment Root Cause Analysis (RCA).....	90
9.2.1	Impairment RCA for Television Model .....	90
9.2.2	Impairment RCA for Videoconferencing Model .....	91
9.2.3	Impairment RCA for General Model .....	92
9.2.4	Impairment RCA for Developer Model .....	93
10.	CONCLUSIONS.....	93
11.	REFERENCES.....	94
APPENDIX A:	SPECIAL SMPTE COLOR BAR .....	97
APPENDIX B:	MULTIPLE DATA SET FITTING (MDSF) ALGORITHM .....	105
APPENDIX C:	ROOT CAUSE ANALYSIS (RCA) EXPERIMENT .....	111

## FIGURES

Figure 1. Steps required to compute VQM .....	3
Figure 2. Temporal indexing of frames in Big YUV files. ....	4
Figure 3. Coordinate system used for sampled luminance Y frames.....	5
Figure 4. Rectangle coordinates for specifying image sub-regions. ....	6
Figure 5. Diagram depicting NTSC interlaced fields and frame/field line numbering scheme.....	9
Figure 6. Spatial shifts considered by the broad search for the temporal shift.....	13
Figure 7. Spatial shifts considered by the broad search for the spatial shift.....	13
Figure 8. Spatial shifts considered by the fine search for the spatial shift.....	14
Figure 9. Special SMPTE color bar for spatial registration. ....	17
Figure 10. Spatial shifts considered by the broad search for the spatial shift.....	18
Figure 11. Spatial shifts considered by the fine search for the spatial shift.....	19
Figure 12. Diagram depicting the method of calculating $TI2(t)$ . ....	30
Figure 13. Diagram depicting the method of calculating $TI4(t)$ . ....	31
Figure 14. Correlation algorithm description.....	33
Figure 15. Example plot of correlation function $S(d)$ . ....	34
Figure 16. Aligned original and processed feature $TI2$ for the scene 5row1 and HRC 2.....	37
Figure 17. Original and processed feature $TI2$ for the scene 5row1 and HRC 11, failed alignment.....	37
Figure 18. Aligned original and processed feature $Ymean$ for the scene 5row1 and HRC 11. ....	38
Figure 19. Original and processed feature $TI2$ for the scene vtc1nw and HRC 24, failed alignment. ....	38
Figure 20. Aligned original and processed feature $TI4$ for the scene vtc1nw and HRC 24. ....	39
Figure 21. Original and processed feature $TI2$ for the scene vtc1nw and HRC 18, failed alignment. ....	39
Figure 22. Original and processed feature $TI4$ for the scene vtc1nw and HRC 18, failed alignment. ....	40
Figure 23. Original and processed feature $Ymean$ for the scene vtc1nw and HRC 18, failed alignment. ....	40
Figure 24. Aligned original and processed feature $TI10$ for the scene vtc1nw and HRC 18. ....	41
Figure 25. Example spatial-temporal (S-T) region size for extracting features.....	49
Figure 26. Overview of algorithm used to extract spatial gradient features. ....	50
Figure 27. Edge enhancement filters.....	50

Figure 28. Division of horizontal (H) and vertical (V) spatial activity into $HV$ (left) and $\overline{HV}$ (right) distributions.....	52
Figure 29. Illustration of the Euclidean distance $euclid(s, t)$ for a two-dimensional feature vector.....	56
Figure 30. Clip subjective quality vs. clip $VQM_T$ .....	73
Figure 31. HRC subjective quality vs. HRC $VQM_T$ .....	74
Figure 32. Clip subjective quality vs. clip $VQM_v$ .....	75
Figure 33. HRC subjective quality vs. HRC $VQM_v$ .....	76
Figure 34. Clip subjective quality vs. clip $VQM_G$ .....	77
Figure 35. HRC subjective quality vs. HRC $VQM_G$ .....	78
Figure 36. Clip subjective quality vs. clip $VQM_D$ .....	80
Figure 37. HRC subjective quality vs. HRC $VQM_D$ .....	81
Figure 38. Clip subjective quality vs. clip $VQM_p$ .....	83
Figure 39. HRC subjective quality vs. HRC $VQM_p$ .....	84

## **TABLES**

Table 1. Full Sub-Region Y, CB, CR Values.....	25
Table 2. Buffered Sub-Region Y, CB, CR Values .....	25
Table 3. Recommended Values for Thresholds Used by Alignment Algorithm.....	35
Table 4. Spatial Collapsing Functions and Their Definitions .....	58
Table 5. Temporal Collapsing Functions and Their Definitions.....	59
Table 6. Technical Naming Convention Used for Video Quality Parameters .....	60
Table 7. Pearson Linear Correlation Coefficients Between Subjective Data and VQM <sub>T</sub> .....	74
Table 8. Pearson Linear Correlation Coefficients Between Subjective Data and VQM <sub>V</sub> .....	76
Table 9. Pearson Linear Correlation Coefficients Between Subjective Data and VQM <sub>G</sub> .....	78
Table 10. Pearson Linear Correlation Coefficients Between Subjective Data and VQM <sub>D</sub> .....	81
Table 11. Pearson Linear Correlation Coefficients Between Subjective Data and VQM <sub>P</sub> .....	84